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FINAL TECHNICAL REPORT

PARTICLE COMPUTATIONS OF
HYPERSONIC SHOCK INTERACTION FLOWS

AFOSR GRANT F49620-01-1-0003

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Grant Monitored By
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Abstract

Development is described of a hybrid DSMC/CFD code for physically accurate and numerically efficient computation of hypersonic, viscous-interaction flows. Recent studies focus on the application and assessment of a hybrid code to a blunted cone configuration and to improvement of physical models used in the code.

Introduction

The interaction between the bow shock of a hypersonic vehicle and the shock waves from a wing or control surface are of great interest in vehicle design because of the potentially high localized temperature and the associated extremely high heating rates in the interaction region. Due to the tremendous technical difficulties and costs in obtaining laboratory and flight measurements under realistic conditions, numerical methods play an important role in the design of new hypersonic vehicles. Computational Fluid Dynamics (CFD) is the most suitable computational approach for the lower altitude portions of a hypersonic vehicle trajectory and for those parts of the vehicle with large physical length scales. The direct simulation Monte Carlo method (DSMC) [1] is a more appropriate technique for rarefied conditions that may be encountered at high altitude or on parts of the vehicle with small length scales, such as a cowl lip. Each of these techniques has their strengths and weaknesses in terms of physical accuracy and numerical efficiency.

Objective

The primary objective of this work is to develop a hybrid DSMC/CFD code for physically accurate and numerically efficient computation of hypersonic interacting flows. The work is being performed in collaboration with Professor Graham Candler who is funded under a parallel AFOSR grant.

Approach

There are three critical steps in the development of a hybrid CFD-DSMC code: (1) identifying when to switch between the methods; (2) communication of information between two very different simulation methods; and (3) integration of these methods into a single, numerically efficient computer code. In our research, we are considering generic hypersonic interacting configurations such as flow over cones, wedges and cylinders to study these issues.

Progress

Our hybrid particle-continuum method is based on an established explicit method for solving the Navier-Stokes equations on the continuum side [2], and a variant of the DSMC technique on the particle side. To communicate information between the DSMC and CFD codes, we use an approach that we originally developed for micro-scale gas flows called the DSMC-IP method [3]. In the DSMC-IP method, the DSMC particles are given both their usual microscopic information and some macroscopic "preserved" information of density, velocity, and temperature. The usual DSMC procedures are followed to change the microscopic information and conservation equations are solved to change the macroscopic information. The DSMC-IP method has proved very successful at reducing the significant statistical fluctuations encountered in the application of pure DSMC to low-speed micro-scale gas flows. One key component of the IP method is that a special model had to be developed to address difficulties in the treatment of translational energy flux. Bearing in mind that the energy flux model had been developed for low-speed flows, we were nevertheless hopeful that the IP component could also provide a physics based filter to reduce statistical scatter in the transfer of information between the DSMC technique and CFD. The CFD and DSMC-IP regions of a flow field are identified using a local Knudsen number continuum breakdown parameter [4]. Buffer cells are used within the CFD region to accurately sample DSMC-IP particles from the Chapman-Enskog distribution function. More details of the approach are provided in Ref. 5. Several enhancements to the original hybrid CFD-DSMC-IP code have been accomplished this year for application to hypersonic flows of interest including implementation of an axially symmetric algorithm, implementation of an implicit CFD solver, and full parallelization of the combined algorithm. The new hybrid code was evaluated through its application to blunt cone and cylinder-flare configurations in Ref. 5. The performance of the code is illustrated here with reference to the blunt cone for which the flow conditions are as follows: Ma=11.3, T=144 K, V=2,765 m/s, ρ=5.223 x 10^{-4} kg/m^3, Tw=297 K. These conditions correspond to Run 31 in the CUBRC code validation database [6]. The geometry considered is the tip of the first cone of the double-cone geometry actually tested at CUBRC in Run 31.

The hybrid simulation procedure is to first run a full CFD computation. Based on this result, an initial distribution of DSMC-IP and CFD domains is established using the continuum breakdown parameter. The CFD and DSMC-IP components of the hybrid method are then initialized using the full CFD computation. Then, as the hybrid simulation proceeds, the CFD and DSMC-IP domain locations are re-evaluated and allowed to evolve. The initial and final domains are shown in Fig. 1(a) in which the CFD regions are in white, and the DSMC-IP regions in gray. The DSMC-IP method is applied in the regions of the shock front and immediately adjacent to the body surface, accounting for about 73% of all cells for this condition. A comparison of contours of translational temperature obtained with a full DSMC simulation and the hybrid code is provided in Fig. 1(b). In general, good overall agreement is obtained between the two solutions.

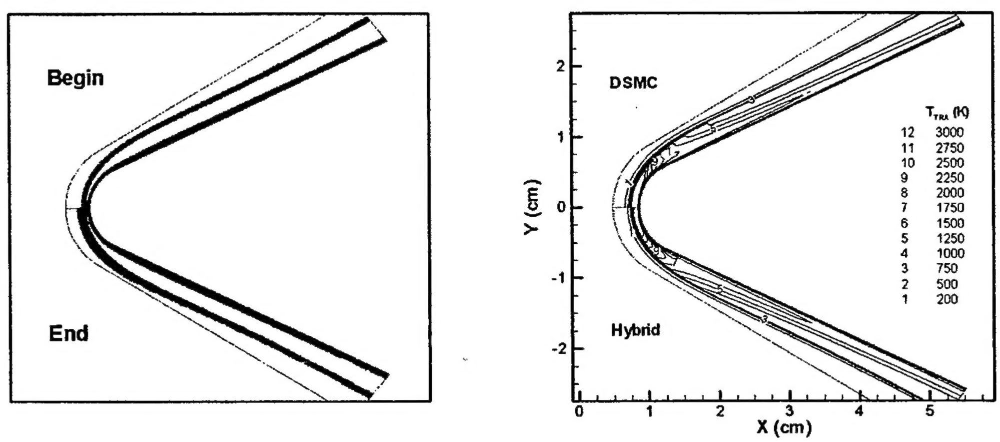

Figure 1. Results for the tip of the blunt cone of CUBRC-Run 31: (a) CFD (white) and DSMC-IP (gray) domains; (b) translational temperature contours (taken from [5]).

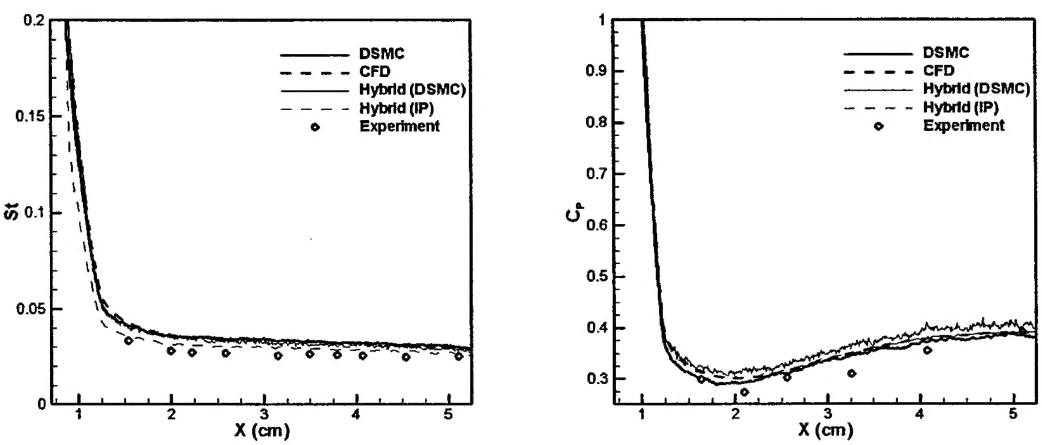

Figure 2. Surface profiles obtained for the tip of the blunt cone of CUBRC-Run 31: (a) Stanton number; (b) pressure coefficient (taken from [5]).

Comparisons of pure CFD, pure DSMC, hybrid results and experimental measurements [6] for the surface properties of Stanton number and pressure coefficient are provided in Figs. 2(a) and 2(b), respectively. Note that two sets of data are produced in the DSMC-IP regions of the hybrid code: one from DSMC, and one from IP. There is excellent agreement in this case between all of the data sets.

As mentioned earlier, one area of concern with the use of the hybrid CFD-DSMC code originally developed for subsonic micro-scale flows for simulation of hypersonic flows, is the treatment of translational energy flux in the IP method [3]. The simplified model that was found to be adequate for subsonic almost iso-thermal flows [3] was found to incur significant limitations in shock waves [7]. Figures 3(a) and 3(b) show profiles of flow

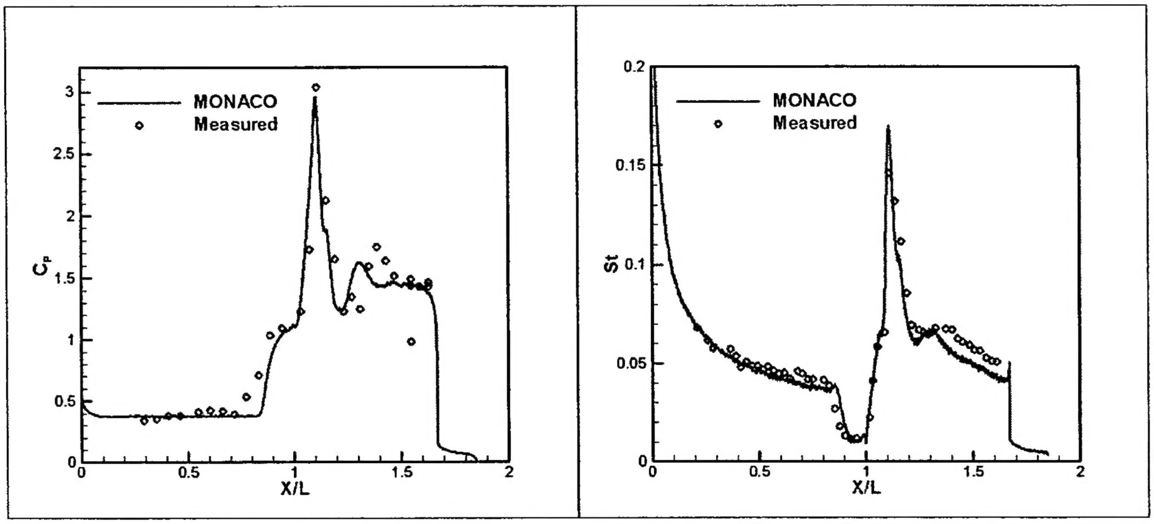

Figure 4. DSMC (MONACO) surface properties for a low-density double-cone configuration (CUBRC Run 7): (a) pressure coefficient; (b) Stanton number.

Future Work

Several aspects of the existing hybrid code require further development. First, the breakdown parameter does not always successfully predict regions where the CFD approach fails. Second, the present code simulates a perfect gas and so thermochemical nonequilibrium models must be implemented. Finally, the numerical performance of the hybrid code must be improved substantially before it is likely to replace pure CFD or pure DSMC computations.

Acknowledgment / Disclaimer

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References

[1] Bird, G.A., *Molecular Gas Dynamics and the Direct Simulation of Gas Flows,* Oxford University Press, 1994.

[2] MacCormack, R.W. and Candler, G.V., "The Solution of the Navier-Stokes Equations Using Gauss-Seidel Relaxation," *Computers and Fluids*, Vol. 17, 1989, pp. 135-150.

[3] Sun, Q. and Boyd, I.D., "A Direct Simulation Method for Subsonic Gas Flows," *Journal of Computational Physics*, Vol. 179, 2002, pp. 400-425.

[4] Wang, W.-L. and Boyd, I.D., "Predicting Continuum Breakdown in Hypersonic Viscous Flows," *Physics of Fluids*, Vol. 15, 2003, pp. 91-100.

[5] Wang, W.-L. and Boyd, I.D., "Hybrid DSMC-CFD Simulations of Hypersonic Flow Over Sharp and Blunted Bodies," AIAA Paper 2003-3644, June 2003.

[6] Holden, M.S., "Experimental Database from CUBRC Studies in Hypersonic Laminar and Turbulent Interacting Flows Including Flowfield Chemistry," June 2000.
[7] Wang, W.-L. and Boyd, I.D., "A New Energy Flux Model in the DSMC-IP Method for Nonequilibrium Flows," AIAA Paper 2003-3774, June 2003.
[8] Chen, P.-H., Boyd, I.D., and Camberos, J.A., "Assessment of Entropy Generation Rate as a Predictor of Continuum Breakdown," AIAA Paper 2003-3783, June 2003.
[9] Harvey, J.K., "A Review of a Validation Exercise on the Use of the DSMC Method to Compute Viscous/Inviscid Interactions in Hypersonic Flow," AIAA Paper 2003-3643, June 2003.

Personnel Supported During Duration of Grant

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Wen-Lan Wang	Graduate Student, University of Michigan, PhD awarded Jan. 2004
Po-Heng Chen	Graduate Student, University of Michigan, MS awarded May 2002

Publications

Wang, W.-L. and Boyd, I.D., "Predicting Continuum Breakdown in Hypersonic Viscous Flows," *Physics of Fluids*, Vol. 15, 2003, pp. 91-100.

Boyd, I.D., "Predicting Breakdown of the Continuum Equations Under Rarefied Flow Conditions," *Proceedings of the 23rd International Symposium on Rarefied Gas Dynamics*, AIP, Melville, 2003, p. 899.

Wang, W.-L., Sun, Q., and Boyd, I.D., "Assessment of a Hybrid Method for Hypersonic Flows," *Proceedings of the 23rd International Symposium on Rarefied Gas Dynamics*, AIP, Melville, 2003, p. 923.

Wang, W.-L. and Boyd, I.D., "Hybrid DSMC-CFD Simulations of Hypersonic Flow Over Sharp and Blunted Bodies," AIAA Paper 2003-3644, June 2003.

Wang, W.-L. and Boyd, I.D., "A New Energy Flux Model in the DSMC-IP Method for Nonequilibrium Flows," AIAA Paper 2003-3774, June 2003.

Chen, P.-H., Boyd, I.D., and Camberos, J.A., "Assessment of Entropy Generation Rate as a Predictor of Continuum Breakdown," AIAA Paper 2003-3783, June 2003.

Honors & Awards Received

AIAA Associate Fellow-awarded May 2003

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Transitions

Hybrid code developed in this research effort used in ARO-SBIR Phase I project.
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